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INTERACTIVE MUSICAL BIOCOMPUTER: AN UNCONVENTIONAL APPROACH TO RESEARCH IN UNCONVENTIONAL COMPUTING

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Abstract: *Computer music is a truly interdisciplinary field; practitioners are well known for experimenting with new and developing technologies from a wide span of disciplines. Such experimentation is a tradition that stems back to the genesis of computer music, where a mathematician with a musical background programmed an early computer in the early 1950s to play a tune. The area of computer music has since evolved in tandem with advances made in computing technology. We are interested in studying how new unconventional models of computation may provide new pathways for music and related technologies. Unconventional computing develops new algorithms and computing architectures inspired by or physically implemented in chemical, biological and physical systems (e.g., DNA computing, quantum computing, reaction-diffusion and excitable media computing). Until recent years, this area of research has been left untouched by computer musicians. Today, interest and research momentum in unconventional computation is building due to our growing need for different kinds of computers: faster, bigger and non-linear. Resulting from this, in hand with technologies becoming more accessible, projects investigating how unconventional models of computation may be used in music are beginning to emerge. In this paper, we discuss some of these initiatives in order to gain an understanding of how this developing area of computer science may impact future music.*

Keywords: computer music, unconventional computing, biocomputing, memristors.

1. INTRODUCTION

We are interested in investigating ways in which unconventional models of computation may provide new pathways for future music and related technologies. The purpose of this paper is to provide an insight into the field of unconventional computing for computer musicians. The aim is that such an insight might inform readers who are interested, but hesitant to explore the potential of unconventional computing paradigms in their works due to the difficulty of finding schemes to adapt to their needs. We briefly review a selection of unconventional computing schemes used for musical applications.

The structure of this paper is as follows: first we present an introduction to the field of unconventional computing. Next, we review a selection of projects investigating the use of unconventional computing schemes in music. Then, we look to new unconventional computing research, which may hold potential for music. The paper concludes with some final remarks.

2 THE FIELF OF UNCONVENTIONAL COMPUTING

Firstly, let us first look to the genesis of today's conventional computing machine and its relationship with music. The term 'computer' originally referred to large groups of people who followed strict sets of rules to solve a mathematical or logic based problem (Stepney 2012). In the 1930s Alan Turing formalised the behaviour of these 'people-based' computers to create the first stored-program computing model, the *Turing Machine* (Turing 1936). Shortly after this in the 1940s, Von Neumann took inspiration from Turing's works and developed a stored-program computing architecture (Aspray 1990; von Neumann 1945). These two innovations are considered the parents to today's commercial computers, with their underlying concepts remaining relatively unchanged. However, we should note that the idea of building programmable calculating machines has been in the air for quite a while before Turing and Von Neumann. A notable example is Charles Babbage's various attempts at building mechanical calculating engines in the early 1800s (Swade 1991).

During the past 80 years, what we consider to be conventional computation (or Turing computation) has advanced at a rapid speed. Amongst computer scientists, there is a growing consensus that we will one day reach the limit of today's conventional computing paradigms, which is a result of our ever-growing need for new kinds of computers, which would be able to address problems that are cumbersome to address with current digital technologies, such as, for example, self-organisation in non-equilibrium systems (Nicolis & Prigogine 1977). As a result of this, research into new computing models is building in momentum and popularity. Defining what constitutes an unconventional computing scheme is a matter of personal orthodoxy. As an overview, words from Toffoli give a general definition of what an unconventional computing scheme is: *"a computing scheme that today is viewed as unconventional may well be so because its time hasn't come yet-or is already gone"* (Toffoli 1998).

Research into new unconventional computing schemes develops new concept algorithms and computing architectures inspired by or physically implemented in chemical, biological and physical systems. That said, it would be easy to associate unconventional computing to the advanced, but this is not necessarily the case. Developed unconventional computing architectures have harnessed basic processes from natural phenomena because of their naturally efficient and simplistic approach to solving certain types of problems. Current unconventional computing paradigms include, but are not limited to, quantum computing, DNA computing, molecular computing and reaction-diffusion computing (Adamatzky & Teuscher 2006). Researchers state that if the same level of development is mirrored in the advancement of new, unconventional, computation then the *"world of computation will be unrecognisably different from today"* (Stepney 2012).

In regards to music, computing technology has played a pivotal part in its development over the last 80 years, and it is likely that future technological developments will continue to impact music. The field of computer music was conceived during the 1950s, where a computer scientist with a musical background manipulated the architecture of the CSIRAC machine to play a selection of popular melodies (Doornbusch 2004). Since this early interdisciplinary endeavour, advances in computer science have had a significant impact on both the way music and audio media is consumed and produced.

3 UNCONVENTIONAL COMPUTING AND MUSIC

In computer music, there is a tradition of experimenting with emerging technologies. Until recent years developments put forward by the field of unconventional computation have been left unexploited, which is likely due to the field's heavy theoretical nature, complexity and lack of accessible prototypes. Lately, with our pursuit for more efficient and powerful technology increasing, research into unconventional modes of computation has been building momentum and the accessibility of prototypes has been widening. This increased accessibility has enabled computer musicians to begin exploring the potential of emerging unconventional computing paradigms. Below we explore a short selection of the research projects that have started to emerge. The reader is also invited to refer to the special issue of the *International Journal of Unconventional Computing*, volume 10, number 3, which is probably the first volume ever published with a collection of research papers on the topic of unconventional computing in music.

At this early point in the intersection of unconventional computing and computer music, we have identified two trends, or approaches: *algorithmic* and *sonic*. The algorithmic approach relates to how unconventional techniques are harnessed within other disciplines, developing computing architectures that process information in some capacity in order to produce the desired output. For instance, an algorithmic implementation could produce the arrangement of musical sections or create an environment for working and interacting with music. A sonic approach is uniquely attributed to the employment of unconventional computation in music. Here the unconventional computing scheme is exploited to produce sound using various sonification techniques.

3.1 Preliminary Initiatives

"Unconventional computing is chock full of theoretical stuff. There are just a handful of experimental laboratory prototypes. They are outstanding but difficult for non-experts to play with." (Adamatzky 2010). Early adopters of unconventional computing in music faced a myriad of constraints that prevented them from employing genuine unconventional computing schemes. Examples of such constraints include advanced laboratory equipment, specially trained personnel and a sophisticated understanding of the underlying theory. These are likely the reasons why cellular automata (CA) models were the first methods used bridge the two fields: CA are capable of simulating some aspects of biological and physical media that has explored in unconventional computing; e.g., chemical reaction-diffusion.

Cellular Automata (CA) are computer tools that can be programmed to model the evolution of a system over time. A cellular automaton is normally implemented on a computer as a grid of cells. Every cell can exist in a defined quantity of states, which are normally represented as integer number and displayed on the computer screen by colours. To enable the model to evolve, rules are applied to the cells informing them to change state according to state of their neighbourhood. Typically these rules remain the same throughout the model, but this is not necessarily always the case. Initially, at time t=0, each cell is assigned its starting state. The model can then produce a new generation (t=1) of the grid by applying the defined rules. This process can continue for an infinite amount of generations.

The first known composer who used CA in his work was Iannis Xenakis in the mid 1980s (Solomos 2006). Xenakis's piece *'Horos'* used a CA to create an evolution of orchestral clusters. Following the release of this composition, a handful of projects using CA started to appear. One example is Miranda's application of a modelled reaction-diffusion computer to control a granular synthesiser, which he developed in 1992 on a Connection CM-200 parallel computer at Edinburgh Parallel Computing Centre (Miranda 1995). Here, the CA grid was divided into a number of sections, which were each assigned to a sinewave oscillator. The automaton was programmed to model the behaviour of a network of oscillating neurons. Upon the automaton's grid refreshing, the mean average state of each oscillator's area is calculated and mapped to control the frequency and amplitude of a sound partial (synthesised by the respective oscillator). All partials are then combined to create a short burst of sound, lasting for a few milliseconds, referred to as a sound granule. Hence the synthesis technique: granular synthesiser, where a rapid succession of sound granules produces a continuous sound. Each of these granules represents the entire automaton's grid at the respective refresh point. Miranda used this system to generate sounds for a number of pieces of electroacoustic music, including *Olivine Tress*, composed in 1993, which is believed to be the first piece of music to be composed on a parallel computer [36].

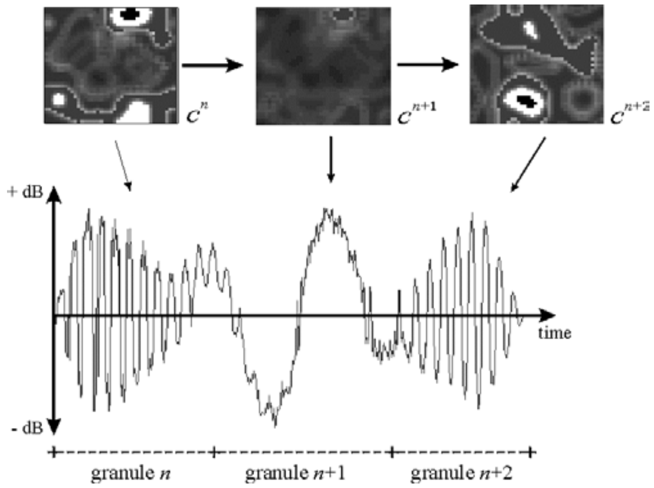

Figure 1: At each time-step, as the cellular automaton evolves it generates parameters to synthesise a sound grain.

CA modelling is an inviting way for computer musicians to experiment with using unconventional computing schemes, but they do have their limitations. For instance, real-time use can be problematic due to the time the grid takes to regenerate and modelling certain systems with accuracy may be problematic. From his various experiments with CA in music, Miranda has suggested that “cellular automata are more suitable for sound synthesis than for musical composition” (Miranda 2007). The reason for this is likely due to musical composition involving aspects of culture and convention, whereas sound synthesis lends itself to the complexity of CA. For other examples where CA have been used in music see (Miranda 1993; Beyls 1989); for an excellent reference Cellular Automata see (Adamatzky 2010).

2.2 Wetware and Hybrid Systems

The continued research in unconventional computing is tightening the coupling between silicon and biological machines. Biological computers harness abstractions derived from biological systems to perform calculations by processing, storing and retrieving data. The first implementation of computational technology based on biological concepts probably was carried out by (Adleman 1994). Since then, there has been a huge amount of interest in biological computing across disciplines. From a musical perspective, biological computing has some very attractive possibilities.

One early project that investigates the feasibility of employing a hybrid wetware-silicon device in computer music is Miranda et al.’s “*Sound synthesis with In Vitro Neuronal*

Networks" (Miranda 2009). In this project the authors were interested in harnessing the spiking interactions between neurons to produce sound. Here, brain cells were acquired from a seven-day-old Hen embryo and cultured in vitro. Culturing brain cells in an in vitro environment encourages them to form synapses – a structure that allows a nerve cell to transmit a chemical or electrical signal to another cell. Once grown, the culture is placed on to a MEA (multi-electrode array) in such a way that at least two electrodes make a connection into the neuronal network. Once arranged, one electrode is arbitrarily chosen as an input into the system and the other, the output. The input is then used to stimulate the network with electrical impulses while the output is used to monitor and record the subsequent spiking behaviour.

With the recorded behaviour, Miranda et al. developed and experimented with a number of sonification methods using additive and granular synthesis techniques to convey the neuronal network's behaviour. In one of these experiments, nine oscillators made up the additive synthesis framework, with the first having its amplitude and frequency controlled directly by the recorded behaviour. The other eight oscillator's parameters are multiples of the first's parameters. Initially, the authors used the gathered behavioural data in its raw, uncompressed form, which produced excessively long sounds. To circumvent this, they implemented a data compression algorithm that retained the target behaviour while removing uneventful data.

The main aim of the project is to create a sound synthesis tool/instrument with a good level of control and repeatability. To achieve this, the authors are considering a machine-learning algorithm aimed at controlling the spiking behaviour of the network. Currently, this part of the project is still in its infancy, but their initial results have shown that they can control spiking behaviour in about one third of cases.

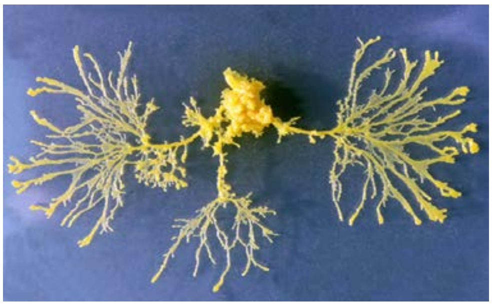

Figure 2: *Physarum polycephalum* is a suitable biological computing substrate.

For most, biological computing schemes such as the before mentioned, may seem out of reach for the average computer musician, but more accessible prototypes are being developed. One example of an emerging biological computing substrate that is openly accessible is the myxomycete, *Physarum polycephalum,* henceforth referred to as *P.polycephalum* (Figure 2).

P.polycephalum, during its vegetative plasmodium phase, exists as an amorphous single cell (visible via the human eye) with a myriad of diploid nuclei, which moves along gradients of chemical and light stimuli. The organism requires comparatively fewer resources and specialist skills to exploit than most other biological computing substrates. The Plasmodium of *P.polycephalum* has been used for a wide variety of computations, such as execution of logic gate schemes (Adamatzky & Schubert 2014), colour sensing (Adamatzky 2013**)** and robot manoeuvring (Tsuda *et al.* 2007); (see (Adamatzky 2010) for a collection of computing schemes harnessing *P.polycephalum* and directions for its use).

As a result of *P.polycephalum's* ease of use, Miranda and associates have begun a set of experiments investigating how its astonishing computational properties can be harnessed for computer music. The first of these experiments is Miranda et al.'s *"Sound Synthesis with Slime Mould of Physarum Polycephalum"* (Miranda *et al.* 2011). Here, a foraging environment is constructed with electrodes embedded into areas containing nutrients. Electrical potentials are recorded from these electrodes as the plasmodium navigates and evolves its state within the foraging environment. After the course of this data collection process, the recorded data is compressed. The resulting data set is then rendered and mapped to control the parameters of a set of oscillators. Each electrode is represented by a sine wave with two controllable parameters: amplitude and frequency. For each data entry, the oscillators produce a sound partial, which represents each electrode's potential at that point. All sound partials are then combined to synthesise a sound, after which the next date entry is put through the same procedure, and so on. This process is continued to synthesise a new sound for every data entry. These are then arranged in order to produce a few minutes of audio. Although this project produced sonically interesting results, which could be used by musicians in several different ways, the time needed to collect the data is tedious and renders the scheme unusable in a live situation. As a result, the problem was addressed by experimenting with a computer approximation of the organism (Jones 2010), which allowed for a real-time implementation of the experiment.

Due to the success of these experiments, and *P.polycephalum*'s accessibility, a handful of other music related projects have emerged, such as the *P.polycephalum* step sequencer (Miranda 2014) and other sonification work (Braund & Miranda 2013). Figure 3 shown an experiment whereby researchers at ICCMR use *P.polycephalum* to grow circuits for a biocomputer for Miranda's composition entitled *Biocomputer Music*, which will be introduced below.

2.3 Physical

The material make up and scheme of our conventional computer's hardware (derived from the von Neumann architecture), in terms of components and logic, has remained relatively similar throughout the years, with the main developments being a reduction in size and heightened efficiency. Recently, there has been extensive research on new computing architectures harnessing different components. In this section of the paper we introduce two areas of current research, which at this time will be out of reach to the average musician, but are likely impact the future of computer science. These are the *quantum computer* and the *memristo*r.

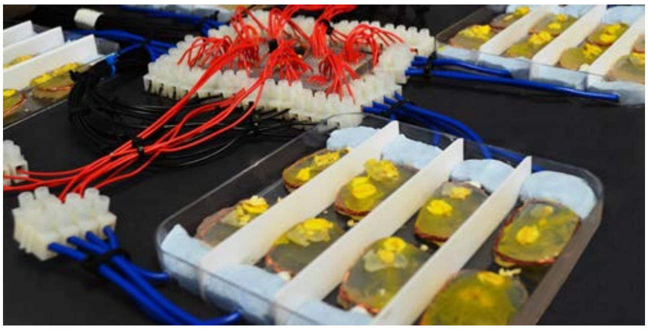

Figure 3: Growing circuit boards for ICCMR's biocomputer.

Quantum computing takes advantage of quantum mechanics to perform computations; e.g., quantum superposition, entanglement and tunnelling. For instance, quantum superposition involves photons being in multiple physical states, e.g. being in multiple locations or representing multiple binary states simultaneously. This super-position ability is a key element behind the promised speed-up of quantum over classical computing.

A quantum computer uses bits like a conventional digital computer, but these are called Qubits and exist in a state of superposition; i.e. can be 1, 0, both or anything in between. Qubits can be made up of any elementary particle, such as photon and electron. In contrast to today's traditional computation, the Qubit's superposition allows a quantum computer to process a massive amount of information simultaneously. Today, there is only one company manufacturing quantum computers and they are prohibitively expensive and large enough to fill an entire office.

The material base of computing architectures has revolved around the three fundamental passive circuit components – capacitor, inductor and resistor. In 1971, Chua theorised a forth fundamental component, the memristor (Chua 1971), which related electric charge and magnetic flux linkage. This component was recently discovered by HP labs (Strukov 2008), and has since been exciting groups of computer scientists due to its potential to revolutionise the material basis of computation. The memristor changes its resistance according to the amount of charge that has previously run through it. Also, in contrast to the other fundamental circuit elements, it is non-linear. As a result of its resistance function, by applying voltages across the component's terminals, a memory of previous states can be accessed. Memristors have also been discovered to exhibit similar characteristics to the way neurons communicate: memristors respond to changes in input by spiking in a similar way to synapses.

In relation to music, Gale et al. have worked on using simulations of memristors to build an analogue computing scheme that aims to go beyond the use of Markov chains for the generation of music (Gale 2013). This scheme exploits memristors for their spiking response to changes in input, memory, time-dependence and non-linearity. To implement this a memristor network was built for musical notes over two octaves, in which every possible note transition is represented by a memristor. The fully connected network is reflective of a completed k-graph where nodes are notes and each vertex a memristor. Note transitions are produced by a memristor spiking in current, which is recorded via an ammeter in series. A separate network produces each note's duration where each node represents a duration and each vertex the transition from one duration to the next. In relation to a Markov chain, in this simulation, the likelihood of a transition occurring is related to the connectivity of each memristor.

Since HP labs announced they had built the first memristor, researchers across disciplines have been keen to experiment with them. Unfortunately, memristors are not commercially available yet and are not easy to manufacture. As a result of this lack of accessibility, researchers began investigating alternative ways to develop their work. Fortunately, it turns out that an array of organic systems exhibit memristive characteristics. Examples of such systems include human blood (Kosta *et al.* 2011), human skin (Johnsen *et al.* 2011) and Aloe vera plants (Volkov *et al.* 2014). More recently, the myxomycete *P.polycephalum* has been discovered to display memristive qualities (Pershin *et al.* 2009) and with its easy of use and accessibility, is a good candidate to explore using memristive functions.

At ICCMR we are looking into ways of building an analogue computing circuit to generate musical accompaniments that encompass components grown from *P.polycephalum*. Currently, we have developed and are experimenting with a preliminary device, which we refer to as a biocomputer. The system takes ideas derived from (Gale *et al.* 2013), which we adapted and further developed to generate arrangements of notes. Miranda has used the biocomputer to compose *Biocomputer Rhytms*, an experimental piece for piano and percussion. The biocomputer listens to the pianist and generates musical responses in real-time, which are played the same piano through electromagnets that set its strings into vibration and vibrates various percussion instruments (Figure 4).

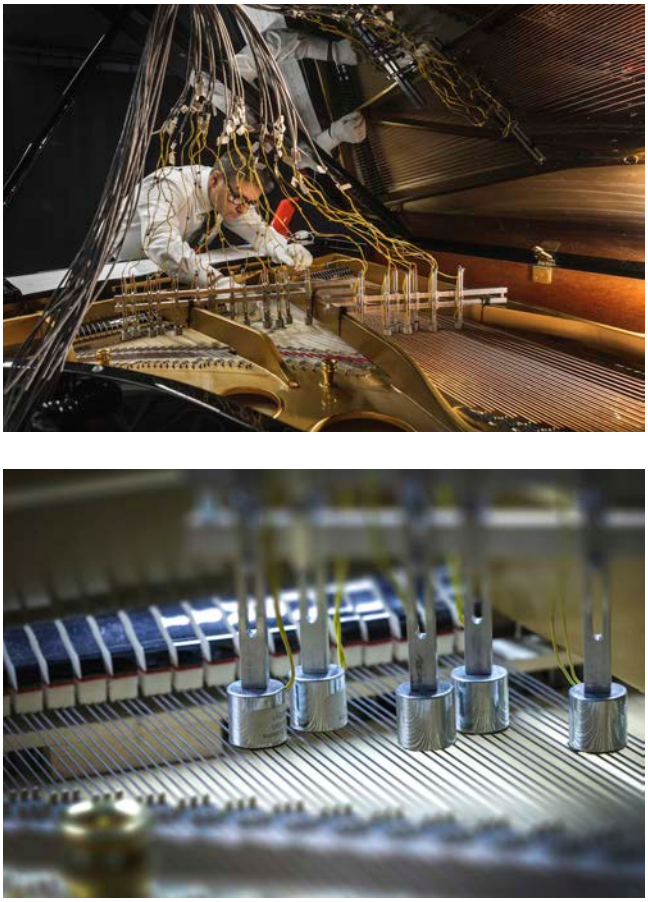

Figure 4: Top: Composer Eduardo R. Miranda preparing the piano for the biocomputer. Bottom: The biocomputer plays the piano through electromagnets placed close to the strings.

Biocomputer Rhythms is scheduled for performance at Symmetry Festival 2016 in Vienna (Figure 5).

4 CONCLUDING REMAKS

This paper has presented an insight to the intersection of music and unconventional computation. Currently, unconventional computing in music is in its infancy, with most existing projects still in the proof of concept stage. For instance, the biocomputer we developed at ICCMR is currently primitive and perishable, but the initial results have shown great promise. Moreover, real-world application projects, such the *Biocomputer Rhythms* composition, which will be performed professionally in a public music festival is certainly a step ahead towards paving the future of this *emerging new music technology*.

Figure 5: The authors (Edward Braund on the left and Eduardo R. Miranda on the piano) fine tuning the biocomputer prototype for a rehearsal of *Biocomputer Rhythms* at ICCMR's BioMusic lab.

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